A STUDY OF THE SYNTHESIS OF A LARGE COMMUNICATIONS APERTURE USING SMALL ANTENNAS

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ABSTRACT

The Jet Propulsion Laboratory is currently engaged in a study to develop a quantitative understanding of the performance, cost, and technical risks associated with synthesizing a large aperture from an array of smaller aperture antennas. The array will be a receive-only system, operating simultaneously at S-band and X-band. This Small Aperture Array Study will parameterize costs of the entire array as a function of the antenna element diameter for a prescribed G/T (gain divided by system noise temperature). As a benchmark, the prescribed G/T will be that of a small number of Deep Space Network 70m antennas (one to three). in this paper, the costs for the antenna subsystem are parameterized. The entire system cost parameterization is available elsewhere.

1. INTRODUCTION

The Jet Propulsion Laboratory is currently engaged in a study to develop a quantitative understanding of the performance, cost, and technical risks associated with synthesizing a large aperture from an array of smaller aperture antennas. Such an array would support the communications links to spacecraft engaged in planetary and solar system exploration. 'l'his study represents the conceptual explorat ion of a part icular evolut ionary path that is open to the Deep Space net work, The array will be a receive only system, operating simultaneously at S-band and X-band. The product of the study is an analytic mode] that relates the total system cost to the diameter of the elemental apertures for a given G/T (i.e., total antenna gain divided by total system temperature). As a benchmark, the prescribed G/T will be that of a small number of 1)eep Space Network 70m antennas (one to three). Costs for the complete system will be parameterized. These include the antennas, radio and intermediate frequency amplification, signal distribution, combiner electronics, and the monitor and control needed to operate the array in a synchronous fashion. This paper documents the results of the antenna subsystem cost analysis.

2. ANTENNA COST MODEl ,

'l'he antenna system is an obvious and major component in the overall array cost model. As will be detailed, the antenna system will be divided into subsystems that include all mechanical and struct ural components, the foundation, and microwave optics (including the feed system, but not includi ng any electronic packages). To simplify the cost estimation process and keep it within a limited time and budget, "off the shelf" technology is to be used for each subsystem. It was decided to contract to two companies specializing in antenna ground station design and fabrication so that detailed antenna subsystem costs could be supplied, and that the estimated costs would not bc speculat ive. These two companies arc

TIW Systems, inc., Sunnyvale, CA, and Scientific Atlanta, inc., Atlanta, GA (SA). The two companies have previously supplied JPL with antenna systems, and therefore are familiar with the specific requirements and procedures of the DSN. Specific tasks that the contractors were to complete areas follows:

- For eight antenna diameters ranging from 3 to 35 meters, production techniques will be investigated and a preferred design for each antenna subsystem will be specified.
- 'l'he design will include specifying antenna optics for each antenna size based on cost, manufacturability, and performance.
- Each subsystem will be further divided into non-recurring and recurring costs.
- Because of the large number of antennas that could be fabricated (especially at the smaller diameters), it is expected that an economy of scale will be encountered. This cost study should outline breakpoints in production where costs drop for a given diameter as more antennas are fabricated.
- To assist in the probabilistic determination of the number of antennas needed to maintain a prescribed G/T margin, the cost estimates should outline antenna components which critically affect reliability, and detail the costs of critical components as a function of reliability.

Due to the limited time and budget of the contracts, the last three items were not examined in great detail. The costs in this section therefore do not reflect any reductions that may be gained by mass production of antenna systems specifically designed for this DSN array application.

3. ANTENNA SPECIFICATIONS

‘l’he number of antennas needed to synthesize the G/T of a 70m antenna is a function of the diameter and system noise temperature of the antennas. Shown in “J’able 1 is the range of the number of antennas needed for each of the eight diameters specified to the contractors. The column of minimum units corresponds to cooled amplifiers and enough antenna elements to comprise one station, while the maximum number of units corresponds to uncooled amplifiers and enough elements to comprise three stations. This range was specified to allow for economics of scale in production methods to surface, and for a complete parameterization of the antenna-amplifier system based on system noise

Table 1. Minimum and Maximum Antenna Elements

Diameter (m)	Units	
	Minimum	Maximum
3	545	27,000
5	196	1(),()()()
10	49	2,500
15	2.2	1,100
20	12	615
25	8	394
30	5	2.74
35	4	201

temperature and antenna diameter. Common sense dictates that an array of inexpensive 3-meter antennas using expensive cooled amplifiers, as well as expensive 35-meter antennas using inexpensive uncooled amplifiers, should produce extremes in the cost model, These extremes would be expected to bound the cost model.

The antenna optics are broken into two regimes, For small diameter antennas, a frequency selective subreflector is used to separate S-band- arranged as a prime focus system- from X-band, which is arranged in a Cassegrain system. For larger diameter antennas, both bands operate in a Cassegrain system, with the bands separated by either a dual-frequency (concentric) feed, or a frequency-selective surface (13S) diplexor. It was expected that the break would occur in the range of 10- 20-meter antenna diameters. This breakpoint option and frequency-combining method were left to the contractor. TIW arrived at designs which used prime focus S-band designs, including an FSS subreflector, for diameters up to and including 10 meters, and Cassegrain configurations with a dual-frequency feed for diameters of 15 meters and larger. Scientific Atlanta arrived at similar designs but with a breakpoint where the dual-frequency feed is used for diameters greater than 21 meters.

To gain a richer understanding of the antenna system cost model, the antenna was broken into eight subsystems. These are as follows:

- Antenna Support Structure. Designs for all antenna sizes were conventional elevation over azimuth configurations. Due to the range of antenna sizes considered, modifications based on production, shipping, and assembly were made to arrive at a final design.

- Main Reflector Surface. Again, based on antenna diameter, different panel production methods were used in the final design.
- Axis Drive. Includes actuators, drive gearboxes, and bearings.
- Position Control. Includes encoders, motors, cabling, and controls.
- Feed System (Including FSS). As noted above, different feed systems were used at the diameter breakpoints specified by the contractor.
- Foundation. No below ground enclosure supplied.
- Power Supply. Includes distribution on site.
- Shipping, installation, and Testing. Different strategies for installation and testing were used based on antenna diameter.

Summaries of the designs as well as the cost information are contained in the final reports supplied by the contractors.

4. PERFORMANCE REQUIREMENTS

The performance requirements specified to the contractors are those contained in the JPL DSN Document 810-5, Volume 1: Existing DSN Capabilities. The specifications necessary for this study are listed in Table 2.

5. THE ANTENNA COST MODEL

Traditionally, antenna cost models have followed a power law

$$C = a + bD_E^x \tag{1}$$

‘l’able 2. Antenna l:lement Specifications

Parameter	Specification
Operating l:requency	l:rom S-band to X-band
Axis Coverage: Elevation Azimuth	 00 to 90° ±200°
Reflector Surface	Solid aluminum
l:nvironments: Precision Operat ion: Wind Rain Temperat ure Normal Operat ion: Wind Rain Temperat ure Survival: Wind Seismic Hail Temperat ure Drive-to-Stow	 1() mph gusting to 12 mph 2 inches pcr hour 0°l: to 115°1: 30 mph gusting to 36 mph 2 inches pcr hour 0°1:101 15°l: 100 mph (stowC(t) 0.3 G horizontal and ().15 G vertical Up to 1-inch-diameter stones -2001 : to 18001~ 60 mph
Maximum Tracking Rates: Velocity Accelerat ion	 0.4°/sec 0.4°/sec²
Maximum Slew Rates: Velocity Acceleration	 ().40/see 0.2°/sec²
Site 1 .ocation	Australia
Soil Conditions	3,000” psf bearing capacity at 3 feet below grade (no piles required)
Axis Configuration	l:levation over azimuth

Table 2, Antenna Element Specifications (Continued)

Parameter	Specification
Pointing Accuracy: Precision Operation Normal Operation	 0.1 beamwidth 0.2 beamwidth
Surface Accuracy: Precision Operation Normal Operation	 0.030-inch” RMS 0.035-inch RMS
Concrete Foundation	Minimum height (no building room required)

where a represents a constant fixed cost, b is a constant, and D_E is the dish diameter. The exponent x is the critical parameter in the cost model, driving costs as the antenna size increases. This parameter has been previously estimated by examining costs of existing antennas and fitting the above power law to the data. One early estimate[1] gave x as 2.78, and this number has been widely quoted. in this study we will fit the above power law to the overall antenna element cost, but will also examine the subsystem costs using fits appropriate for the subsystem. For example, the feed subsystem does not have to increase with dish diameter, but may show step function breaks when changing from prime-focus S-band system to dual-frequency Cassegrain systems.

Figure 1 shows the cost estimates from the two contractors for the antenna elements as a function of diameter. Scientific Atlanta supplied data for more diameters than specified because they have existing systems or cost data at 13,16, 18,21, and 32 meters. The SA data is not as smooth as the TIW-supplied cost data

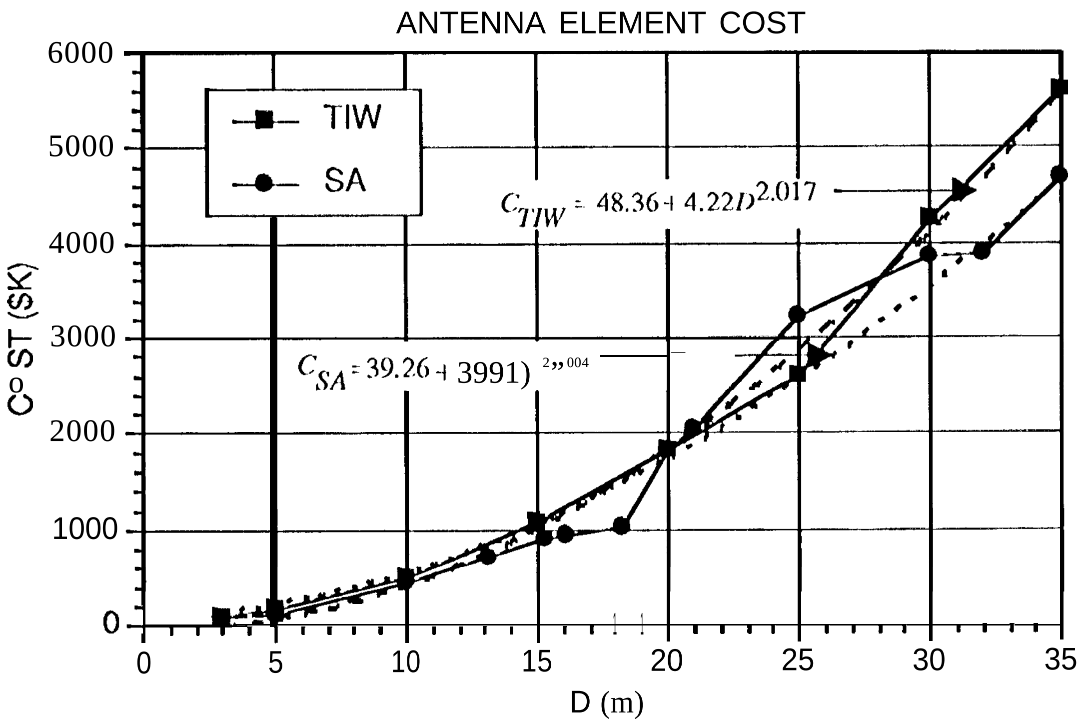

Figure 1. Total antenna clement cost and power law fits to data.
Costs in fits to data arc in units of $K.

because of design variations at some diameters. Specifically, SA supplies an 1 8-meter system where the structure, foundation, and shipping, installation, and test subsystems are optimized for cost.

Power law fits to the data arc also shown on the plot. For both data sets, it is seen that the cost increases as the diameter is *squared,* counter to higher powers previously published. It is interesting to note that the Project Cyclops study[2] came to the same conclusion for 25-meter to 150-meter antennas. The fact that antenna costs scale as diameter is squared profoundly affects the overall conclusions of this study.

6. **ANTENNA SUBSYSTEM** COSTS

Cost data for the eight antenna subsystems are presented in Figures 2- 9. Costs for specific subsystems at specific antenna diameters are plotted on the charts for both contractors. The circle and square symbols denote the points where data was supplied, and solid lines connect the data points. On each chart, fits have been made to the data, Where appropriate, power law fits have been made; otherwise, step functions arc used to model breaks in the data. For some components it is clear that the SA data does not have an obvious fit to a particular cost model. As mentioned previously, this is due to optimization of certain diameters for cost reduction,

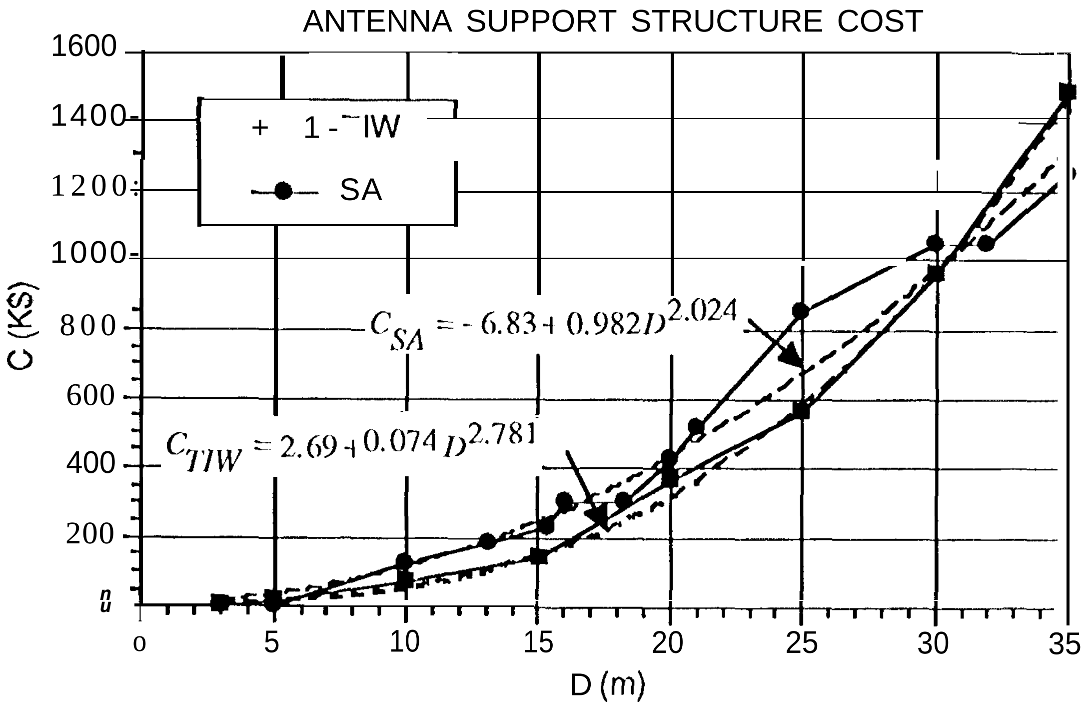

Figure 2. Cost and power law fits to data for antenna support structure.
Costs in fits to data arc in units of $K.

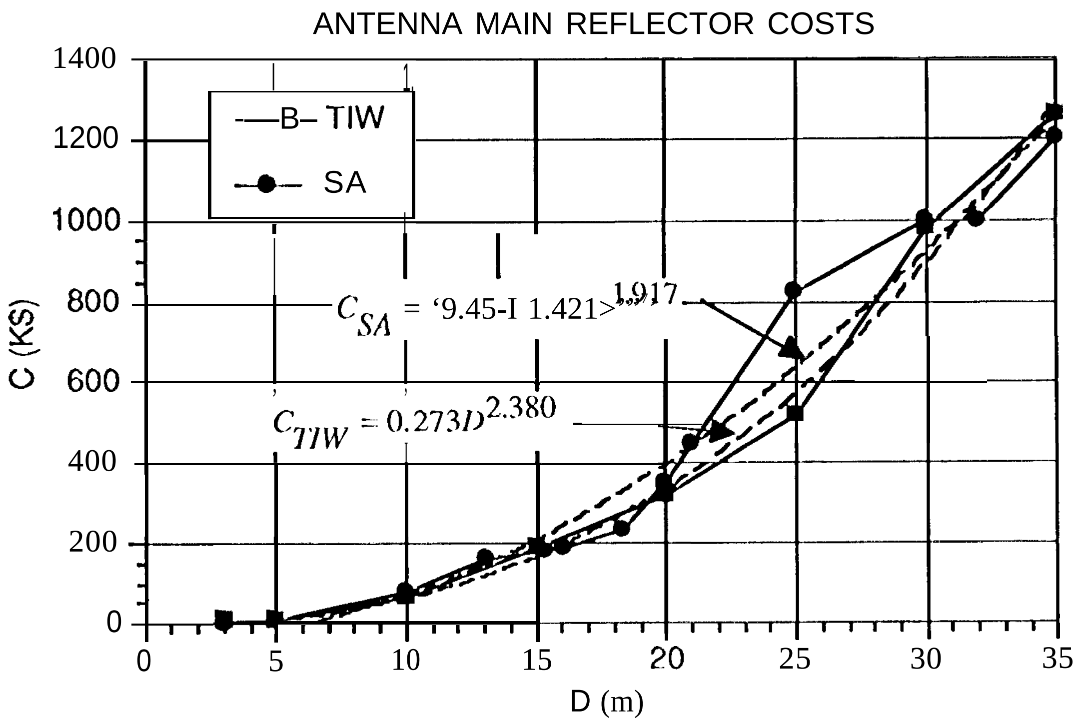

Figure 3. Cost and power law fits to data for antenna main reflector. Costs in fits to data are $K

7. SUMMARY

For the purposes of the overall array cost model, the cost power law fits from Figure 1 are sufficient to model the antenna system. When fit to a power law, the data from the two contractors are remarkably similar:

$$C_{TIW} = 48.36 + 4.22D^{2.017}\ (K\$)$$
$$C_{SA} = 39.26 + 3.99D^{2.004}\ (K\$). \quad (2?)$$

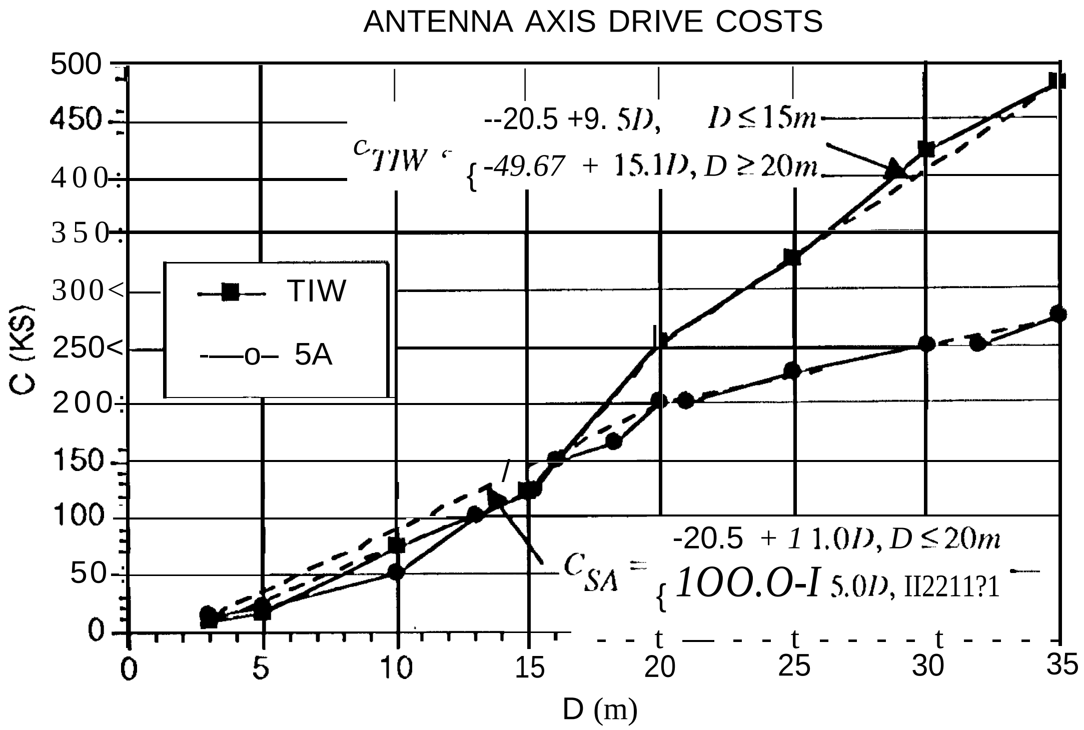

Figure 4. Cost and *fits* to data for antenna axis drive.
Costs in fits to data are in units of $K.

For better local fits to the data, or for individual subsystem cost data, the individual models shown in Figures 2-9 can be used. An antenna system cost model made up of the individual subsystems is then

$$C = C_{SUP} + C_{REF} + C_{AX} + C_{POS} + C_{FEED} + C_{FOUN} + C_{POW} + C_{SIT} \ (K\$) \qquad (3)$$

where the individual subsystem costs are given in the figures.

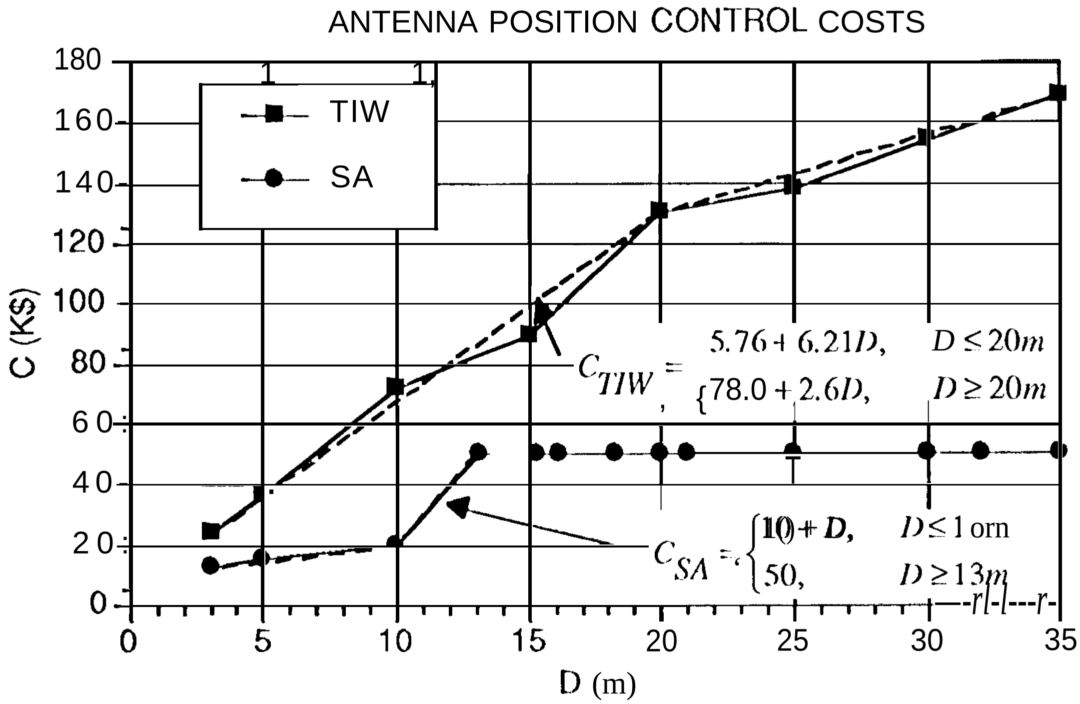

Figure 5. Cost and fits to data for antenna position control.
Costs in fits to data are in units of $K.

It is interesting to break down the costs by subsystem, examining the fraction each subsystem contributes to the total antenna cost, as well as the scaling of each subsystem, Figure 10 is the percent of total cost for each of the eight subsystems for the TIW data. It is seen that structure, reflector, and shipping, installation, and test subsytem costs increase with diameter size; feed, position control, and power subsystem costs decrease, while foundation and axis drive costs are relatively constant. For 3-meter antennas, the feed and position control subsystems contribute 57 % of total cost- this is an obvious area for cost reductions for high quantity production. To extrapolate cost scaling for larger system, the individual cost models (three) were calculated for diameters up to

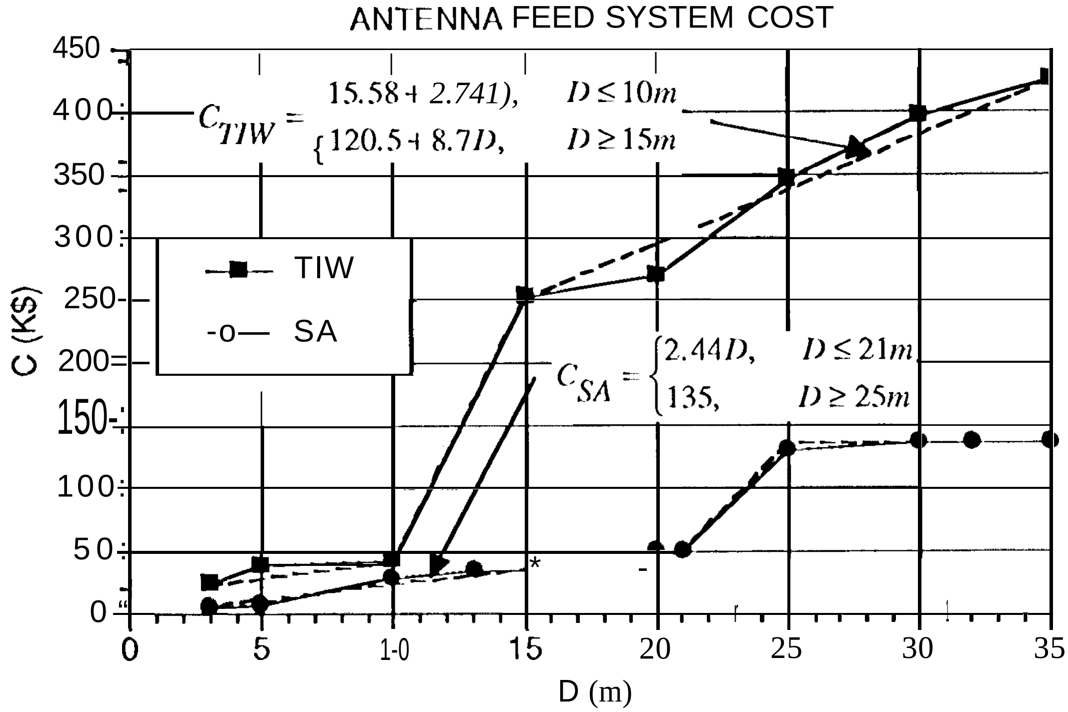

Figure 6. Cost and power law fits to data for antenna feed system, Costs in fits to data are $K.

100 meters. The costs were calculated based on the individual cost models for TIW data in Figures 2- 9 with power law fits made to the resulting extrapolated data. It was seen that when a power law was fit to data up to 50 meters, the cost scaled as $D^{2.27}$; for fits to 70 meters the costs scaled as $D^{2.40}$; and for fits to 100 meters the costs scaled as $D^{2.50}$. These costs are, of course, extrapolations to the small antenna diameter data and are speculative.

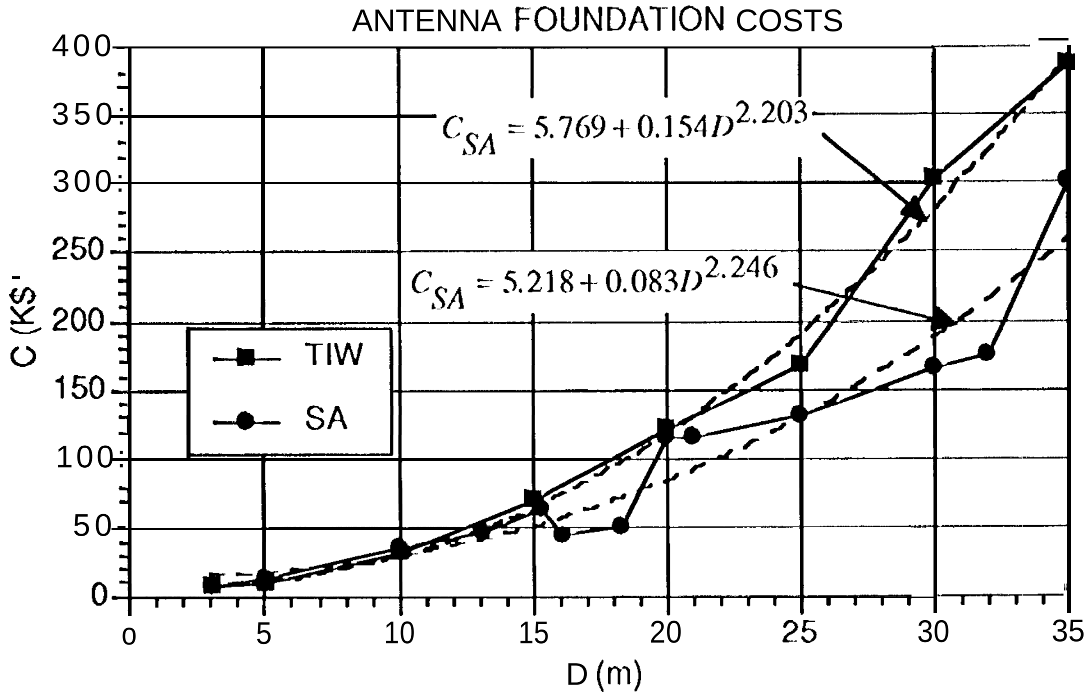

Figure 7. Cost and power law fits to data for antenna foundation subsystem. Costs in fits to data are in units of $K.

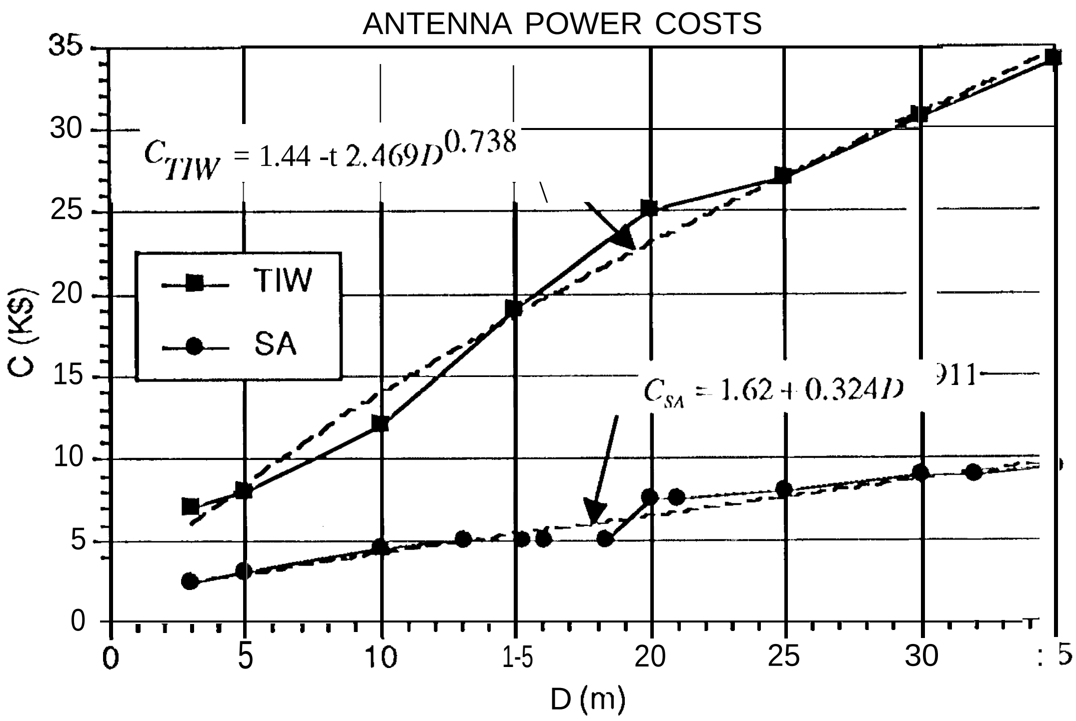

Figure 8. Cost and power law fits to data for antenna power subsystem. Costs in fits to data are in units of $K.

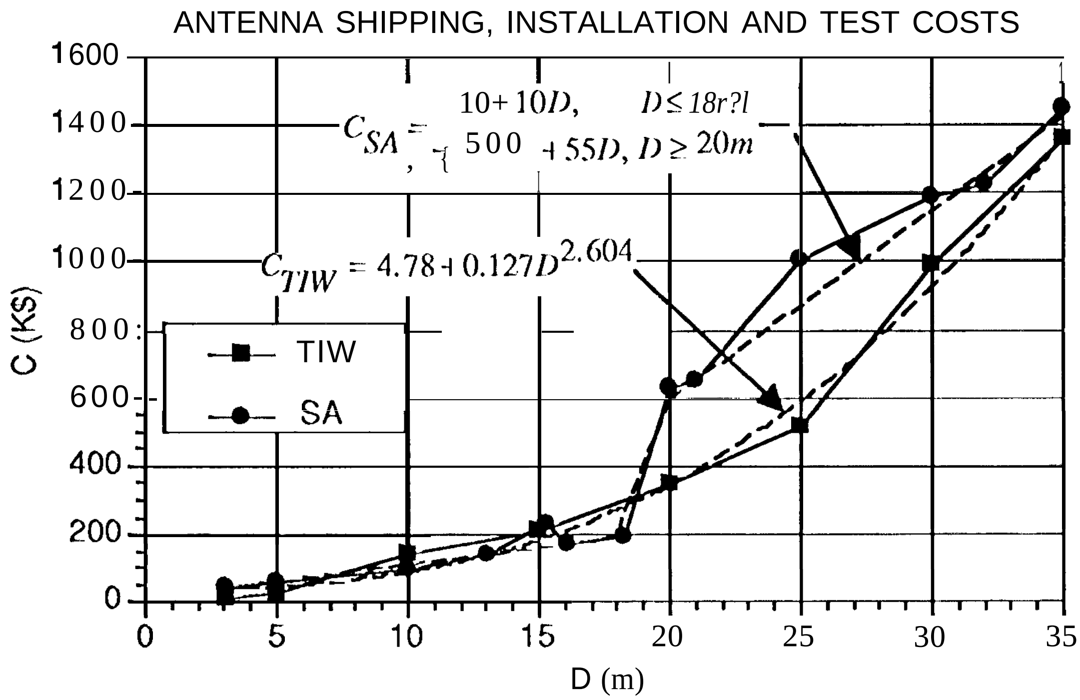

Figure 9. Cost and fits to data for antenna shipping, installation, and testing subsystem. Costs in fits to data are in units of $K.

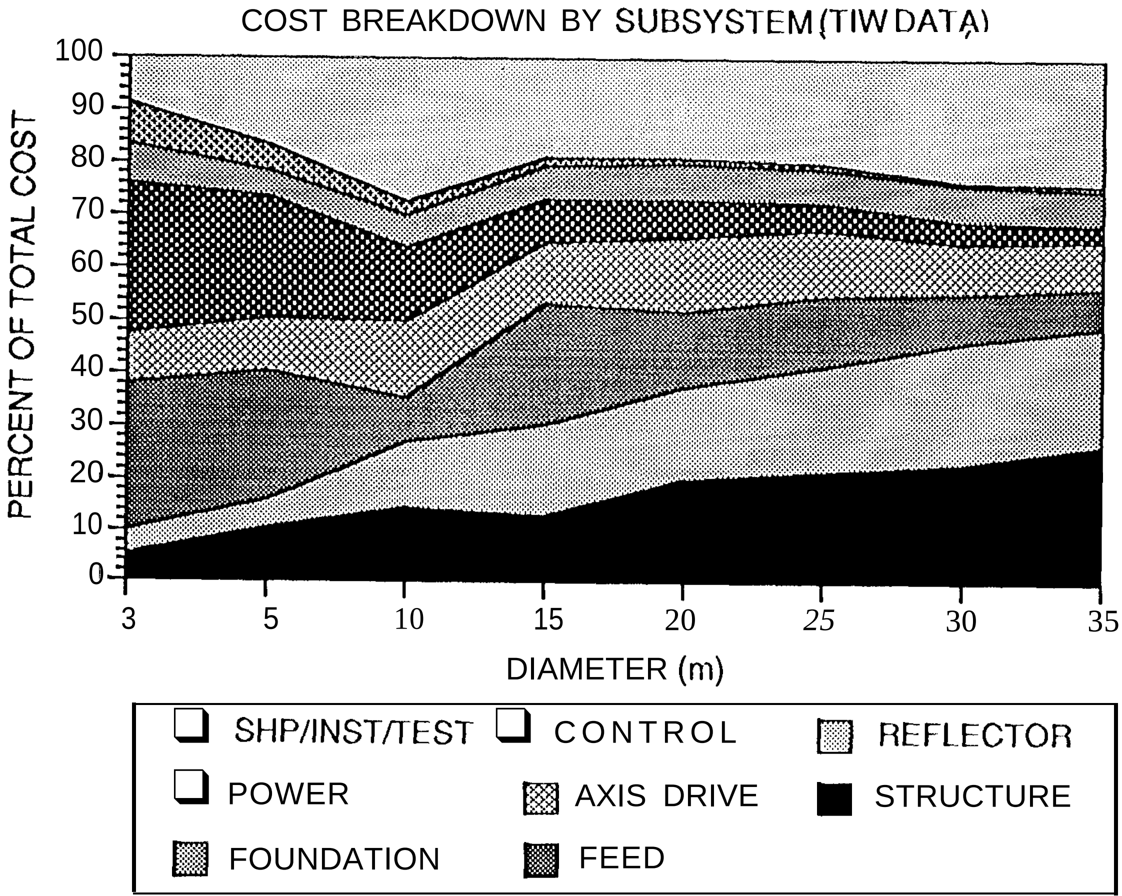

Figure 10. Cost breakdown by subsystem as fraction of total antenna cost.

8. ACKNOWLEDGMENTS

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9. REFERENCES

1. Potter, P.D. (1965) Large Antenna Apertures and Arrays for Deep Space Communications. *JPL Technical Report No.* 32-846'.
2. *Project Cyclops, A Design Study for Detecting Extraterrestrial Life, CR 114445,* NASA/Ames Research Center, 1971.